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Evaluation of an elliptical area technique for calculating mitral blood flow by Doppler echocardiography

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SUMMARY To evaluate a method for measuring blood flow through the mitral valve 18 normal subjects and 19 patients with cardiac disease in whom mitral and aortic blood flows were identical were studied. Initially the mitral ring area was planimetered from the echocardiographic image, but the results of area calculation using the mathematical formula for the area of an ellipse were found to approximate to within 8% of the planimetered result in most cases. The formula was therefore used if the ring appeared elliptical on the cross sectional echo image, and other shapes were planimetered. Mitral velocity, aligned with flow in three planes, was recorded just distal to the ring. Mitral flow calculated using the elliptical technique correlated closely with flow measured in the ascending aorta by the Doppler technique and also with systemic flow measured by the Fick method at cardiac catheterisation in 10 patients.

The mitral flow technique that assumed a circular orifice correlated almost as well with Doppler aortic flow and with Fick flow but overestimated flow by a mean of 1446 ml, whereas the elliptical method had a mean error of only 138 ml. Both methods correlated well with standards, but the elliptical method was easy to apply and gave a better correlation with comparison reference values.

Calculation of flow by the Doppler method requires measurement of the mean velocity of flow, the intercept angle (theta) between the measurement axis and the direction of flow, and the area of the orifice or conduit through which flow is passing. This concept can be expressed as follows: flow = (mean velocity × area)/cosine theta.

In theory the combination of cross sectional imaging and Doppler echocardiography permits measurement of all these variables, and all the information necessary for flow calculation can be obtained from these methods. The reliability of data from various possible flow measurement sites has been the subject of many investigations. Measurement of aortic,[1–3] pulmonary,[2 4 5] and tricuspid[6] blood flow by Doppler echocardiography has been found to be accurate when compared with reference standards. Mitral flow has presented a more difficult problem. The measurement of mitral velocity is relatively simple, but the determination of the area through which flow is passing is much more difficult. Two methods have been used. The first method required imaging the maximal mitral leaflet orifice in short axis and altering that area by a factor derived from measurements of the mitral complex on an M mode recording.[7] Although this method provided accurate flow measurements in dogs, in humans the correlation with flows measured by other methods was poor.[6] This discrepancy was probably related to the different shape of the mitral orifice in the two species. Reports have been published of an alternative method that treats the mitral orifice as a circle.[8 9] This method appears to improve the correlation, but further assessment is needed.

We report a method that provides a more accurate estimate of the area of the mitral orifice and provides a better correlation with reference standards.

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Patients and methods

The study population consisted of 18 normal subjects (aged 3 to 35 years) and 19 children (aged from infancy to 17 years) with a variety of congenital cardiac malformations (Table 1). The selection of patients was determined mainly by the nature of their cardiac lesion. Patients were included if their aortic and mitral flows would be expected to be equal on the

Table 1 *Patient data, mitral valve dimensions, and mitral flow velocities by the various methods*

Case No	*Diagnosis*	*Mitral valve dimension (cm)*	*Ratio**	*Mitral flow (ml/min)*		*Aortic flow† (ml/min)*	*Fick flow (ml/min)*
				Ellipse	*Circle*		
1	Normal heart	3·85×2·07	0·54	3764	7005	3502	—
2	Normal heart	4·32×2·96	0·69	6263	9164	7915	—
3	Normal heart	2·10×1·22	0·58	2007	3458	2217	—
4	Atrial septal defect	3·20×2·60	0·81	4545	5597	5658	—
5	Normal heart	2·37×1·73	0·73	3279	4494	3339	—
6	Normal heart	2·43×2·43	1·00	5238	5238	6224	—
7	Normal heart	3·20×1·80	0·57	4192	7455	4502	—
8	Normal heart	3·50×2·18	0·62	5498	8832	5817	—
9	Normal heart	2·00×1·47	0·74	3461	4712	2810	—
10	Normal heart	1·85×1·44	0·78	2123	2725	2611	—
11	Normal heart	1·60×1·20	0·75	1275	1700	1132	—
12	Persistent ductus arteriosus	2·50×2·02	0·80	4234	5242	3707	—
13	Supraventricular tachycardia	2·30×1·56	0·67	5526	8151	6623	—
14	Normal heart	2·80×2·20	0·79	4369	5564	4663	—
15	Normal heart	4·10×2·90	0·71	7554	10614	7590	—
16	Aortic stenosis	3·50×2·93	0·84	9867	11793	9923	—
17	Postoperative tetralogy of Fallot or ventricular septal defect	3·25×2·40	0·74	4507	6107	4375	—
18	Normal heart	2·80×2·00	0·71	4414	6188	5288	—
19	Normal heart	3·40×2·80	0·82	5945	7223	4905	—
20	Normal heart	2·80×2·00	0·71	5621	7887	4727	—
21	Normal heart	3·00×2·40	0·80	6850	8567	7002	—
22	Normal heart	3·10×2·40	0·77	4450	5751	5359	—
23	Normal heart	2·90×2·20	0·75	6881	9075	6509	—
24	Persistent ductus arteriosus	3·10×2·22	0·72	6089	8486	6615	6400
25	Persistent ductus arteriosus	1·60×1·20	0·75	2437	3245	2796	—
26	Atrial septal defect	2·90×2·20	0·76	3426	4517	3279	3300
27	Pulmonary stenosis	1·90×1·50	0·79	2160	3481	2280	2400
28	Pulmonary stenosis	2·80×2·20	0·79	3438	4317	3213	3200
29	Atrial septal defect	2·55×1·85	0·73	3749	5025	3739	3600
30	Atrial septal defect	2·75×2·20	0·80	2830	3538	3160	—
31	Atrial septal defect	4·00×3·01	0·75	5479	7309	5547	—
32	Postoperative tetralogy of Fallot or ventricular septal defect	1·60×1·25	0·78	1241	1625	1372	—
33	Aortic stenosis	Irregular	—	3349‡	5661§	3160(T)	3000
34	Atrial septal defect	2·40×1·80	0·75	3738	4983	3832	3400
35	Pulmonary stenosis	1·47×1·07	0·73	1241	1341	1372	1100
36	Aortic stenosis	Irregular	—	2430‡	¶	2200(T)	2300
37	Postoperative tetralogy of Fallot or ventricular septal defect	2·45×1·40	0·57	3050	5381	2670	1400

*Ratio of minor to major axis of the mitral valve.
†(T), flow measured at the tricuspid valve.
‡Area determined by planimetry.
§Value calculated from a diameter measurement.
¶Incalculable because of lack of satisfactory diameter measurement.

basis of their known cardiac malformation. Patients with abnormal mitral valves (mitral stenosis or atrioventricular defects) were excluded as were patients with significant aortic stenosis or incompetence. In 10 patients mitral flow was measured simultaneously by the Fick method and by the Doppler technique during cardiac catheterisation.

AORTIC FLOW MEASUREMENT

Aortic flow measured by the Doppler technique or systemic flow measured by the Fick method served as reference standards for mitral flow measured by the Doppler technique. Aortic flow was measured as previously described.[2] An off axis imaging transducer was placed in the suprasternal notch and the cursor aligned with the walls of the mid-ascending aorta. The highest velocity with the least spectral broadening was obtained by manipulation of the transducer within the two visualised planes. The transducer was then moved carefully in the third plane to maximise velocity and reduce spectral broadening. When this manoeuvre was completed the velocity obtained was considered to be the true maximal velocity, and no correction for an intercept angle was used. This same

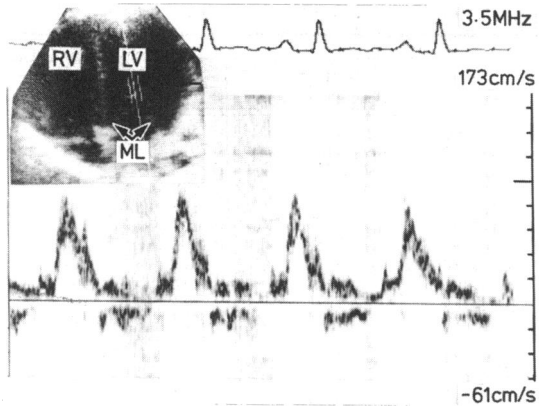

Fig. 1 *Mitral velocity tracing and a cross sectional echocardiogram showing the site from which it was recorded. The cursor is shown as a highlighted imaging line and the sample volume as two parallel lines flanking the cursor. RV, right ventricle; LV, left ventricle; ML, mitral leaflets.*

spatial alignment technique was used for velocity recordings at all other sites. The aortic diameter was measured at the level of the centre of the sample volume by lateral resolution (centre of the brightest portion of the image of one wall to a similar point on the other wall) from the same transducer location in the suprasternal notch and was then converted to an area using the formula: area = 3·1416 × (diameter × 0·5) squared.

TRICUSPID FLOW MEASUREMENT

Tricuspid flow was measured as previously described.[6] From an apical four chamber imaging plane, a spatially aligned velocity was obtained just distal to the tricuspid ring. The tricuspid orifice diameter was measured between the insertions of the valve leaflets on to the ring and the diameter was converted to an area by applying the same formula as for the aorta.

MITRAL FLOW MEASUREMENT

Mitral velocity was recorded from the apical four chamber imaging plane by placing the sample volume just distal to the ring and generally aligned with the septum. The optimal transducer location was one that placed the septum vertically within the imaging cone (Fig. 1) or one in which the apical septum tilted slightly to the right. The sample volume was located approximately at the leaflet commissure. A site with large amplitude negative velocities (from the left ventricular outflow tract) was avoided. The ultrasound beam was then spatially aligned with flow as previously described to record the maximal velocity, an example of which is shown in Fig. 1. Mean velocity was determined by manually digitising the modal velocity of at least three cardiac cycles on a digitising pad interfaced to an Apple II computer. The modal velocity is the most commonly occurring velocity at any given instant and appears therefore as the blackest part of the time-velocity trace (Fig. 1). The computer, which was controlled by a dedicated Biodata program, was used to determine the area enclosed by the time-velocity curve and to calculate mean velocity per second by dividing this area by the distance along the horizontal axis. This process has been described in detail.[10] To measure the mitral ring diameter the transducer was placed in the parasternal short axis plane, and the root of the aorta, including the cusps, was imaged. The transducer was then angled slightly inferiorly and leftward to image the mitral ring. The ring was usually elliptical, but sometimes the posterior right area was slightly flattened.

The valve rings were photographed from a video tape recording. Although the ring size did not change much with the cardiac cycle it was considerably easier to measure in early diastole because the leaflet tissue was displaced into the ventricle. The axes were measured from the monitor using a manual caliper, and then that distance was measured with electronic calipers. This method provided increased accuracy and control compared with primary measurement with electrical calipers. The major axis was measured by lateral resolution and the minor axis by the leading edge technique. The major axis measurement provided data essentially the same as measurement of the ring orifice from the four chamber plane, and this value was used for the calculation of mitral valve area by the circle method.

Initially, images were recorded of 20 such orifices and the area determined by planimetry. The results were compared with those of the area calculated according to the formula: area = a × b × 3·1416, where a is the major axis and b the minor axis measured perpendicular to the mid-point of the major axis. The results of the area calculation were within 8% of the planimetered area if the ring was approximately an ellipse or a flattened ellipse. If the ring was scalloped or irregular, however, the calculated and planimetered areas differed by 10% to 20%. Therefore for this study all scalloped or irregular rings were planimetered and the area of all the regular rings was determined by the formula. In both instances the accepted value was the mean of at least three beats. The time required to obtained appropriate velocities and area measurements in a cooperative subject was 3–4 minutes.

STATISTICAL ANALYSIS

The results of the various measurements of mitral, aortic, and Fick blood flows were compared by linear regression analysis and paired *t* test.

Results

Data of adequate quality were obtained from all patients selected for study, and no imaging or velocity recording proved to be particularly difficult.

MITRAL RING SHAPE

The mitral rings were found to vary in shape. One normal subject and two patients had orifices that were clearly neither an ellipse nor a flattened ellipse. The normal subject had a ring that was essentially circular. The two patients had rings with significant scallops. The remainder had rings that were approximately elliptical or flattened ellipses. The range of the ratio of minor to major axis, excluding the subjects with the round or irregular orifices, was 0·54–0·84 (mean 0·73). Most subjects had a ratio near 0·75 (Table 1).

COMPARISON OF MITRAL AND AORTIC DOPPLER FLOW MEASUREMENTS

Aortic blood flow measured by Doppler was recorded in 35 subjects. Two others had turbulent flow in the aorta, and therefore, in these patients, since no shunts were present tricuspid flow measured by the Doppler technique was substituted for aortic flow (Table 1). Mean mitral flow by the elliptical technique for 37 patients was 4230 ml/min (Table 2), which was not significantly different from mean aortic flow (4368 ml/min). Mean mitral flow by the circular technique (36 patients), however, was 5874 ml/min, which was significantly greater ($p<0·01$) than aortic flow (mean 4428 ml/min) in the same patients.

Comparison of mitral flow, calculated by the elliptical method, with aortic flow (including the two patients with tricuspid measurements) measured by the Doppler technique gave a correlation of 0·96; SEE 516 ml; slope 0·90; intercept 297 ml (Table 2, Fig. 2). Mitral flow calculated by the circle technique and compared with the same group showed a correlation of 0·91; SEE 1003 ml; slope 1·13; and intercept 868 ml (Table 2, Fig. 2).

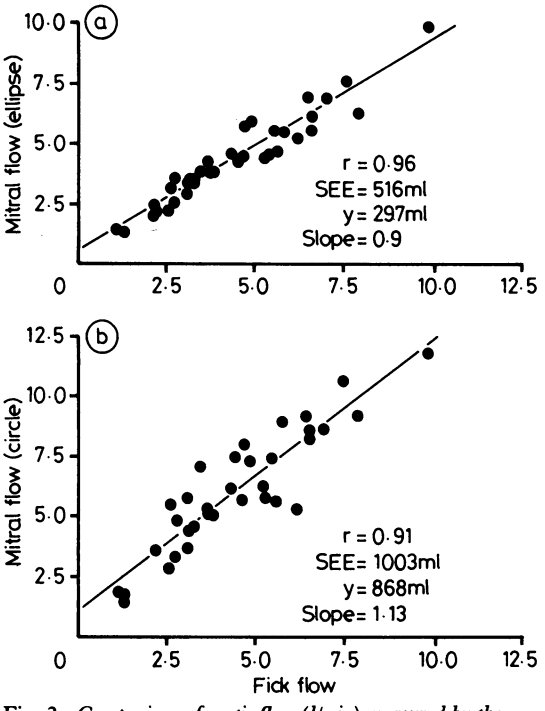

Fig. 2 *Comparison of aortic flow (l/min) measured by the Doppler technique and mitral flow (l/min) measured by (a) the elliptical and (b) circular area techniques. r, correlation coefficient; SEE, standard error of the estimate; y, value of the intercept on the vertical axis.*

COMPARISON OF DOPPLER AND INVASIVE FLOW MEASUREMENTS

Mean values for flow in 10 patients by the mitral elliptical (3267 ml/min), aortic (3236 ml/min), and Fick (3010 ml/min) methods were not significantly different (Table 2). The mean value for flow calculated by the mitral circular method in nine patients (4799 ml/min) was considerably greater than that by the Fick method in the same patients (mean

Table 2 *Comparison and correlation of flow values through the mitral and aortic valves*

Method	*n*	*Mean (SD) (ml/min)*	*p*	*r*	*SEE (ml)*	*Slope*	*y axis intercept (ml)*
Mitral flow (ellipse)	37	4230(1871)	NS	0·96	516	0·9	+ 297
Aortic flow	37	4368(1998)					
Mitral flow (circle)	36	5874(2465)	<0·01	0·91	1003	1·13	+ 868
Aortic flow	36	4428(1992)					
Mitral flow (ellipse)	10	3267(1271)	NS	0·93	435	0·81	+ 825
Fick flow	10	3010(1461)					
Mitral flow (circle)	9	4799(1896)	NS	0·82	1024	1·02	+1656
Fick flow	9	3088(1527)					
Aortic flow	10	3236(1407)	NS	0·96	370	0·93	+ 450
Fick flow	10	3010(1461)					

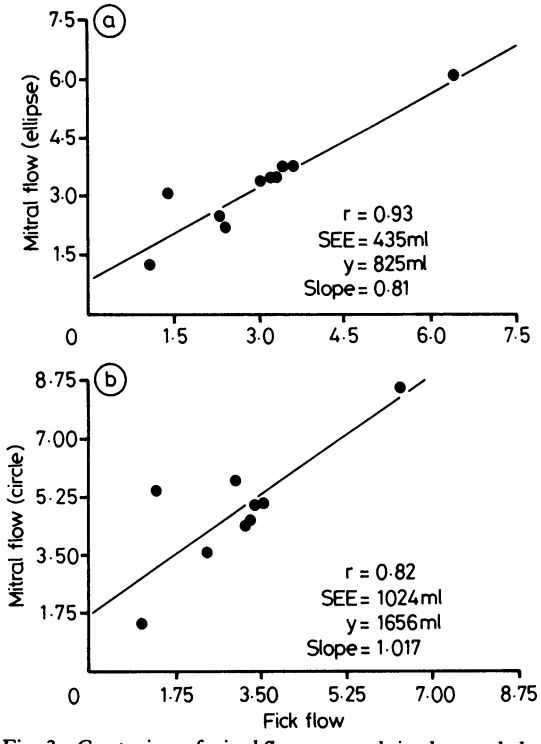

Fig. 3 *Comparison of mitral flow measured simultaneously by the Fick method at catheterisation and by the Doppler technique with the mitral area calculated by (a) the elliptical and (b) the circular area methods. Abbreviations and calibration of axes as in Fig. 2.*

3088 ml/min), but the difference was not statistically significant. The three Doppler flow measurements (mitral elliptical, mitral circular, and aortic) all correlated well with Fick flow (Figs. 3 and 4, Table 2) with

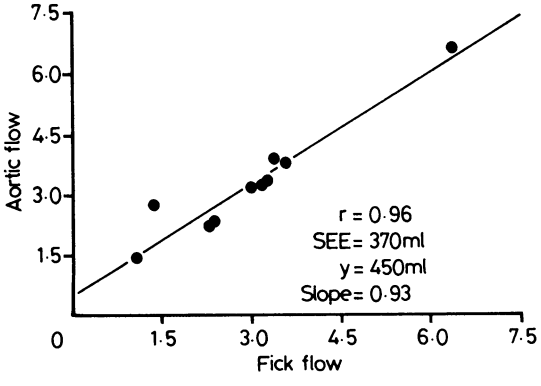

Fig. 4 *Comparison of flow measured simultaneously at catheterisation by the Fick method and by the Doppler technique in the mid-ascending aorta. Abbreviations and calibration of axes as in Fig. 2.*

correlation coefficients of between 0·82 and 0·96, the lowest correlation being for the comparison of the mitral circular method with Fick flow. Other descriptive statistics were different (Table 2). The standard errors of the estimate were: aortic (370 ml), mitral elliptical (435 ml), and mitral circular (1024 ml). The slope of the relation was very close to 1·0 for the mitral circular method but was significantly lower for the aortic and mitral elliptical techniques. The intercept was closest to the origin for aortic flow (+450 ml) and further for mitral elliptical (+825 ml) and mitral circular (+1656 ml).

Discussion

Three main findings emerge from this study: *(a)* mitral flow determined by either of the two evaluated techniques correlated reasonably closely with control flows, *(b)* mitral flow calculated by the elliptical orifice area technique provided a closer match with control flows than did mitral flow calculated by the circular area technique, *(c)* aortic flow measured by Doppler correlated closely with Fick flow and had the lowest standard error of the estimate of any of the Doppler measured flows.

MITRAL ELLIPTICAL TECHNIQUE

Brock observed that in the living patient the mitral annulus was not usually circular,[11] and careful assessment using cross sectional echocardiography confirms that, although the shape of the mitral annulus changes throughout the cardiac cycle, the orifice is essentially elliptical.[12] Anatomical studies have usually been performed by dividing the valve annulus and measuring the circumference rather than defining its precise shape. Rusted and colleagues showed that in a small number of adults the mean anteroposterior diameter of the mitral valve was 1·5 cm compared with an intercommissural diameter of 2·5 cm for men and of 2·1 cm for women.[13] As they pointed out, however, the anteroposterior diameter could not be measured with the same degree of accuracy as the intercommisural diameter because of the way in which the valves had been opened. Figure 5 shows the shape of three typical mitral valve orifices, two in fresh postmortem specimens and one as seen from the parasternal short axis view using cross sectional echocardiography.

In most of the patients in the present study the orifice appeared to be a flattened ellipse, whereas in a few other patients it was irregular in shape containing angles or scallops (Table 1). Only one subject had a mitral orifice that was approximately circular. The valve ring was more difficult to image than the leaflets, but its shape and size were relatively constant throughout diastole whereas the leaflet orifice varied

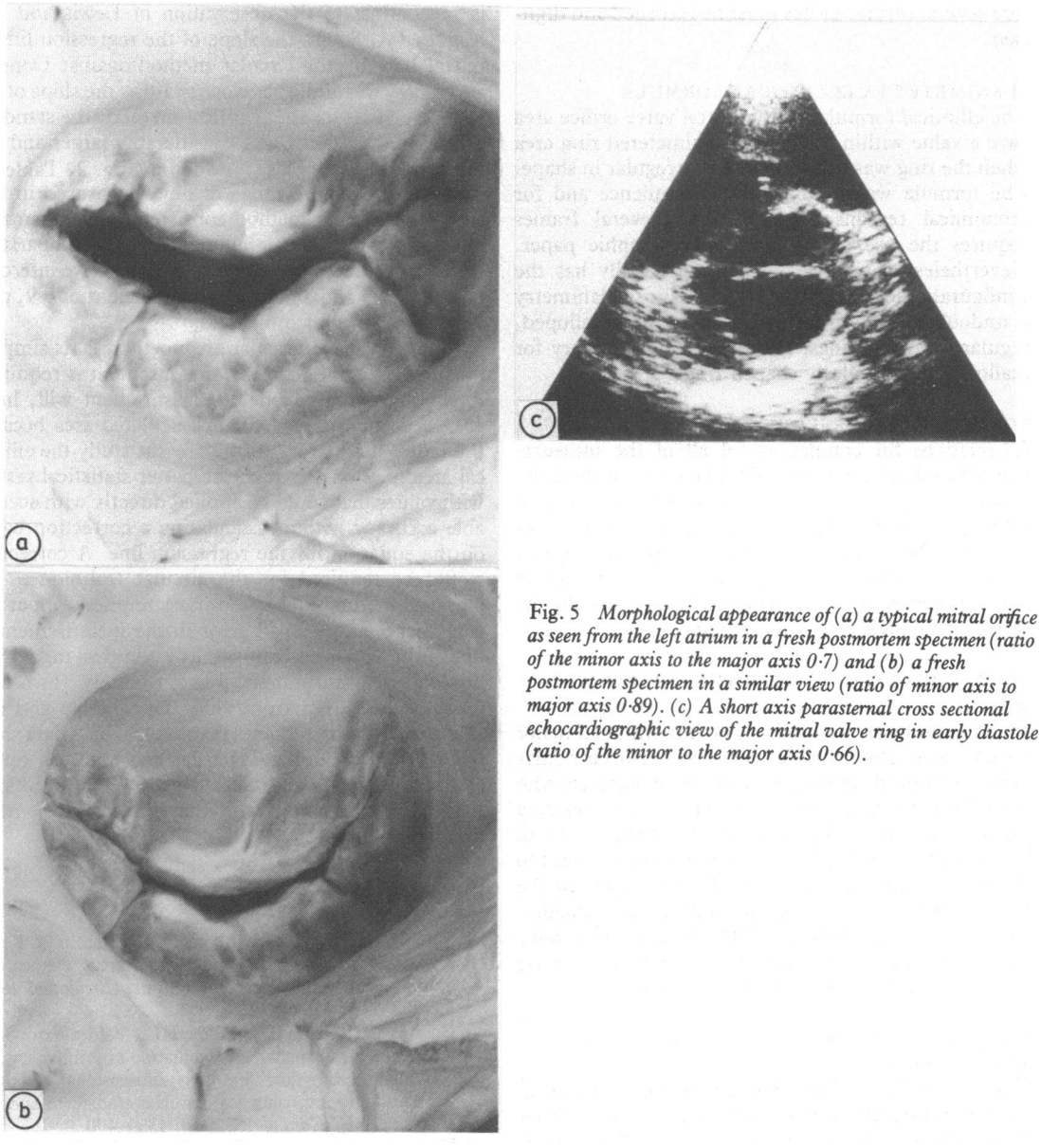

Fig. 5 *Morphological appearance of (a) a typical mitral orifice as seen from the left atrium in a fresh postmortem specimen (ratio of the minor axis to the major axis 0·7) and (b) a fresh postmortem specimen in a similar view (ratio of minor axis to major axis 0·89). (c) A short axis parasternal cross sectional echocardiographic view of the mitral valve ring in early diastole (ratio of the minor to the major axis 0·66).*

continuously. Essentially, the same shape and area can be measured from the leaflets near their insertion into the annulus, but this area constantly changes and equals or nearly equals the ring area only during early diastole. A true short axis image of the ring or the first portion of the leaflet is essential because imaging in any other plane might introduce angulation and foreshortening of one or the other of the axes.

MITRAL VELOCITIES

The correct cursor alignment needed to record maximal velocity with minimal spectral broadening of the signal may not parallel the septum, and the exact site must be determined by listening to the audiosignal and observing the monitor. Mitral velocity patterns are not identical from beat to beat and depend on cardiac cycle length and phase of respiration. There-

fore several cardiac cycles must be recorded and digitised.

PLANIMETRY *VS* ELLIPTICAL FORMULA

The elliptical formula for the mitral valve orifice area gave a value within 8% of the planimetered ring area when the ring was not scalloped or irregular in shape. The formula was used for its convenience and for economical reasons since printing several frames requires the use of expensive photographic paper. Nevertheless, since the mitral ring usually has the configuration of a slightly flattened ellipse planimetry is undoubtedly more accurate even for non-scalloped, regular bordered rings. Planimetry is mandatory for scalloped or irregularly shaped rings.

CORRELATION COEFFICIENTS

Correlations for comparison of all of the measurements in this study were high. The range of the data, however, was necessarily large because children of different ages were studied. A large range of values improves the correlation coefficient. If the range of values was reduced, as might occur in a study of an adult population, the same technique would be expected to have a lower correlation.

ERRONEOUS RESULTS WITH THE ELLIPTICAL METHOD

This method was not used in patients who had major mitral valve abnormalities such as atrioventricular defects or mitral stenosis. Furthermore, subjects who have the mitral valve in an unusual site may present a problem in proper alignment of the ultrasonic beam with the plane of the ring. This situation could lead to an underestimation of the area if one or other of the measurement axes was foreshortened. Finally, patients with calcification of the annulus may have increased reflections that might impede precise assessment of the valve ring dimensions.

COMPARISON OF THE THREE METHODS FOR MITRAL FLOW

Since all methods share the same velocity measurement the differences in calculated flows result from the differences in the way in which the flow area is calculated. The initial technique described by Fisher and associates[7] provided a reasonably accurate assessment of mitral flow in dogs, but when data were compared with other techniques in humans the correlation coefficient with aortic flow was less than 0·6 and the standard error of the estimate exceeded 1 l/min.[6] Preliminary results suggest that the circular area technique provides an improvement in both these respects.[8 9] In the present study, however, the circular method consistently overestimated mitral flow because the orifice was rarely a full circle. This finding is in contrast to the observation of Lewis and colleagues.[9] Although the slope of the regression line of mitral flow by the circular method against Doppler aortic flow was almost as close to 1·0 as the slope of the regression line for the elliptical method, the standard error of the estimate was considerably larger and the intercept on the y axis was 868 ml (Fig. 2, Table 2). Therefore, over the range of flows measured in this study the circular method consistently overestimated mitral flow to a considerable degree. By comparison, the elliptical method, with a smaller positive intercept on the y axis and a correlation coefficient of 0·9, provided a better match of flows.

In favour of the circular area method is its simplicity since only one diameter measurement is required. A slight error in diameter measurement will, however, lead to a large error in calculated area because the radius is squared. In the present study the elliptical area method provided the better statistical results with values that could be applied directly with acceptable accuracy without calculating a correction based on the equation for the regression line. A correction would be required for the circular technique. The elliptical method makes fewer assumptions about the ring shape, and a small error in the measurement of one of the axes is less critical. The elliptical method is, however, slightly more difficult to apply. Two axes must be measured from video tape replay and any shape irregularity requires planimetry. The data show that, although both the circular and elliptical mitral area techniques have clinical value, the best results are found for mitral flow with the elliptical area measurement method.

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